BIOLOGICAL PRODUCTIVITY AND MATERIAL TRANSPORT IN THE SEA OF OKHOTSK

NAKATSUKA TAKESHI
Institute of Low Temperature Science, Hokkaido University

In Chapter 1 of this paper, I describe the physical and chemical characteristics of the Sea of Okhotsk which should be related to the biological productivity in the Sea of Okhosk, and then in Chapter 2, I present the results of biological and chemical flux studies conducted during the previous joint Japan-Russia-US expeditions in Sea of Okhotsk from 1998 to 2000 for understanding the status of present our knowledge on the biogeochemistry in the Sea of Okhotsk. Some parts of Chapter 1 are also based on the results obtained during the joint expeditions.

1. CHARACTERISTIC MARINE ENVIRONMENTS IN THE SEA OF OKHOTSK AND THEIR IMPLICATIONS FOR BIOLOGICAL PRODUCTIVITY

The Sea of Okhotsk is known as the lowest latitudinal area in the world where seasonal sea-ice can be produced every year (Alfultis and Martin, 1987; Kimura and Wakatsuchi, 2000). The sea ice always extends to 44°N every winter which is corresponding to location of southern France in Europe. Its extraordinary severe feature of the Sea of Okhotk regardless of its low latitude is caused by following two factors. One is the existence of East Siberian Continent as the Cold Pole of the northern Hemisphere. From this land mass adjacent to northwest area of the Sea of Okhotsk, strong winter monsoon blows southeastward in winter, producing large amount of sea ice along the northwestern coast of the Sea of Okhotsk (Martin et al., 1998). The sea ice is transported to southern and eastern area of the Sea of Okhotsk by the wind and the strong western boundary current "East Sakhalin Current" (Ohshima et al., 2002). The other factor is the fresh water discharge from Amur River. Amur River is ranked in the ten largest rivers in the world, and discharges about 300km^3 of fresh water into the Sea of Okhotsk every year (Ogi et al., 2001). Because of the semi-closed morphology of the Sea of Okhotsk, the fresh water stays on the surface water for a long time and creates strong halocline at subsurface layer, which prevents the surface water from mixing with deeper layer. In the ocean, sea water can be hardly frozen because the seawater at frozen temperature has higher density than warmer seawaters and the active vertical convection should continue until all the water mass from surface to bottom become the frozen temperature, meaning that the seawater cannot be frozen by the cooling in only one winter. However, in the case of the Sea of Okhotsk, the strong halocline helps the surface water to be frozen by separating the surface water from the deeper water.

The sea ice accelerates a positive feedback loop in the Earth climate because the sea ice produced in a cold atmospheric environment reflects larger parts of solar radiation than seawater directly to space (high aledo) and it also suppresses the heat exchange between ocean and atmosphere, making the atmosphere much colder. As for the effects of sea ice to primary productions, following direct and indirect effects can be pointed out. First of all, the sea ice is produced in a very cold circumstance in winter. The coldness itself of course suppresses the biological productivity in winter, but on the other hand, it promotes the vertical mixing of water to bring large amounts of nutrients from deeper layer to enhance the primary production in the following season. Sea ice also supports the algal primary production directly. Some of algal species such as diatom are known as "ice algae" which is attached onto the bottom of sea ice in early spring. Because the mixed layer depth in early spring is deeper than the depth which can provide enough solar radiation for the growth of phytoplankton, phytoplankton cannot grow at that time. However, if the phytoplankton is attached on the bottom of sea ice, it can receive plenty of light without being brought to deeper and dark layer. Moreover, sea ice contributes the formation of very thin and stable surface water mass, after sea-ice melting in spring, where phytoplankton can grow very rapidly to form an ice-edge bloom using plenty of light and nutrients there (Sullivan et al., 1988; Niebauer et al., 1995). However, the exact relationship between algae and sea ice has not been clarified yet especially in the pelagic area of the Sea of Okhotsk due to the difficulty of its observation.

The sea ice does not only modify the climate in the atmosphere and the ocean surface, but also change the environment in ocean interior. Because the sea ice itself consists of fresh water, the extremely saline water, brine water, is rejected during the formation of sea ice. Along the northwest coast of the Sea of Okhotsk, large amount of brine water is produced in winter and settles down on the bottom of the continental shelf due to its nature of high density. The dense water mass located on the bottom of the northwestern continental shelf is called as Dense Shelf Water (DSW) and it flows out into the intermediate layer of the deep basins to join the formation of the Okhotsk Sea Intermediate Water (OSIW) according to its moderate density due to very cold but slightly fresher nature than pelagic water masses (Kitani, 1973; Gladyshev et al., 2000; Itoh et al., 2003). Because the density of DSW is the highest in all over the North Pacific area among those of water masses ventilated from local surface layers, the production and ventilation of DSW is believed to be important not only for the production of OSIW but also for ventilation of all the North Pacific Intermediate Water (NPIW) by the connection through Kuril straits between the Sea of Okhotsk and Pacific Ocean (Talley, 1991; 1997; Yasuda et al., 1996; Wong et al., 1998).

The DSW brings large amounts of dissolved and particulate materials into the pelagic area during its negative heat and salt transports. Nakatsuka et al. (2002) found extremely cold and turbid intermediate water masses near the continental slope area of the northwestern Sea of Okhotsk in the summer of 1999 (Fig.1a) . Such cold and turbid water masses have the density of 26.8-27.0 $\sigma\theta$ as same as the DSW, and can be found on the bottom of continental shelf too (Fig.1b). On the bottom of northwestern continental shelf, strong tidal mixing makes a thick homogeneous benthic boundary layer that is the DSW (Kowalik and Polyakov, 1998), where large amounts of particles are entrained from the sediment surface (Fig. 1c). The benthic water mass is not only turbid but also dense with dissolved matter, and those particulate and dissolved organic and inorganic matter are flushed out of the shelf bottom into pelagic ocean interior by East Sakhalin Current and/or Density flow along the continental slopes (Mizuta et al., 2003; Fukamachi et al., 2004). Supplies of those materials actually support the heterotrophic biomasses in the intermediate layer of the Sea of Okhotsk (Sorokin and Sorokin, 1999). This mechanism must be characteristic not only in the Sea of Okhotsk but also in seasonal freezing marginal seas in the world. Interestingly, materials transported into ocean interior with DSW have a chance to be entrained into surface layer again near the Kuril straits because of the strong tidal mixing occurring near the straits. This may be important as a source of terrestrial minor nutrients for the phytoplankton around Kuril islands including Oyashio Current.

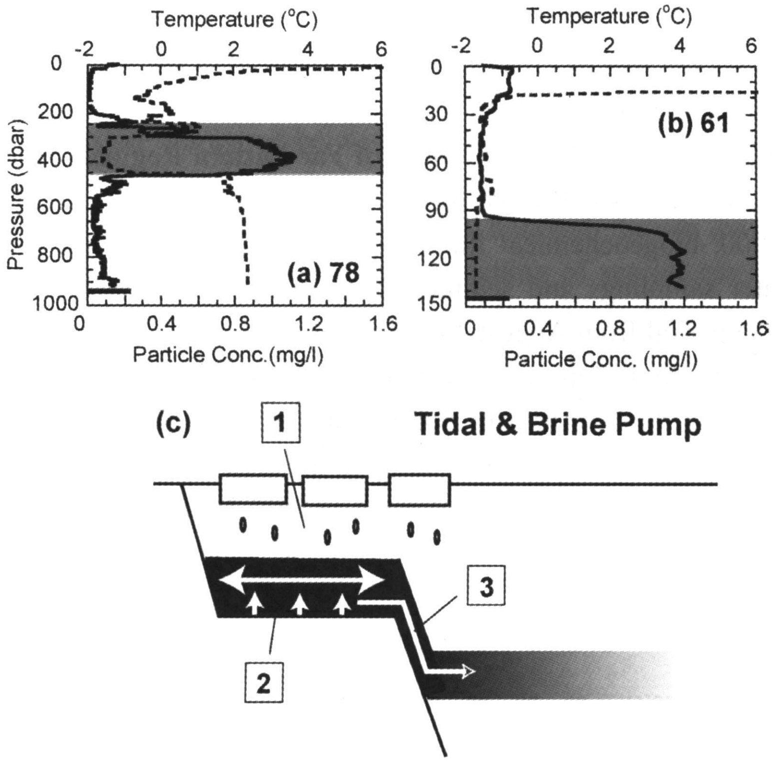

Figure 1. Vertical profiles of the turbidity (solid line) and the temperature (dashed line) at the sites (a) 78 (continental slope) and (b) 61 (continental shelf). (c) A schematic diagram explaining causes of the extremely turbid and cold intermediate water masses in the Sea of Okhotsk (1. Deposition of cold and dense brine waters on the shelf bottom due to the sea ice formation. 2. Resuspension of sedimentary particles into a benthic boundary layer due to a tidal mixing. 3. Outflow of the cold and turbid water masses into the oceanic intermediate layer.)

A biogeochemical characteristic of the Sea of Okhotsk other than the sea ice is the existence of large amounts of major nutrients in the deep layer as well as those of North Pacific Ocean. Because maximum depths of Kuril straits between the Sea of Okhotsk and Pacific Ocean often exceeds 1000-2000m, the deep water can be exchanged between two seas, resulting in the inflow of high concentrations of major nutrients such as nitrate and silicate to the Sea of Okhotsk from Pacific Ocean where global deep water circulation terminates. Contrary to the deep layers, major nutrients in the surface layer of the Sea of Okhotsk are usually depleted during summer, although those of northwestern region of North Pacific Ocean adjacent to the Sea of Okhotsk remain high even in summer characterizing the northern North Pacific as the area of "High Nutrient Low Chlorophyll" (HNLC). The reason why the Sea of Okhotsk is not "HNLC" is still unclear, but Amur River may supply significant amounts of iron, which usually limits primary productivity in the northern North Pacific area, and support the primary productivity in the Sea of Okhotsk, exhausting major nutrients there. Actually in the Sea of Okhotsk, satellite images tell us that high density of phytoplankton always covers the area near the Amur River mouth, suggesting some contributions from materials existing in river discharge (Saitoh et al., 1996).

2. BIOGEOCHEMICAL FLUX STUDIES IN THE SEA OF OKHOTSK (PRESENT & PAST) – RESULTS OF JOINT RESEARCH CRUISES FROM 1998 TO 2000-

In order to clarify the role of Okhotsk Sea Ice controlling the regional and global climate system, Joint Japan-Russia-US research expeditions of the Sea of Okhotsk were conducted from 1998 to 2001 using R/V Prof. Khromov of Far Eastern Regional Hydrometeorological Research Institute, Vladivostok, Russia. At the three research cruises in July 1998, September 1999 and June 2000, biogeochemical flux studies were carried out including sediment trap studies, CTD/Water samplings and sediment core samplings. Sediment trap samples were collected during the period from August 1998 to June 2000 using McLane Mark78G sediment traps with 21 rotating sample cups at two different depths (300 and 1550m, 300 and 700m) of each of two locations (M4: North; M6: South) off northeast coast of Sakhalin. CTD/Water samplings were conducted more than 100 station in the area off Sakhalin and the northwestern continental shelf. Sediment cores were collected in July 1998 using a piston corer at three locations (PC-1: East; PC-2: Center; PC-4: West) in the central basin (Deryugin Basin) of the Sea of Okhotsk (Fig. 2).

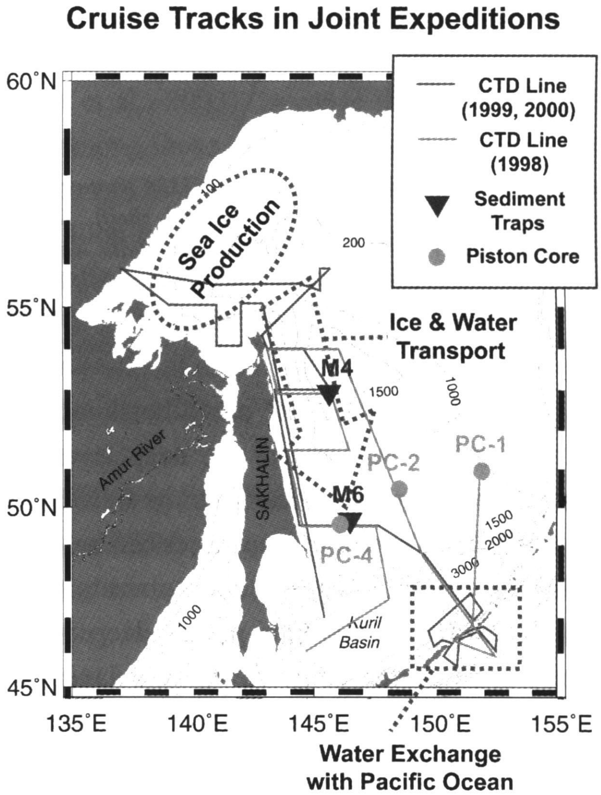

Figure 2. Sites and routes of sediment traps, sediment coring and CTD/Water samples in 1998-2000.

2-1. SEDIMENT TRAPS

In the time-series of sediment trap samples, fluxes of terrestrial inorganic components intermittently increased corresponding to events of abrupt cooling of the intermediate layer (Fig.3) which were revealed by the moored thermistors there (Nakatsuka et al., 2004a). Because the cold water mass in the intermediate layer can be brought there by the outflow of DSW, this coincidence between the cooling of intermediate layer and the increase in terrestrial material flux must be an evidence that DSW actually transport large amounts of particulate matter from continental shelf area to pelagic region. Fluxes of biogenic opal which correspond to those of diatom showed bimodal seasonal variations increasing in late spring and early summer similar to those observed in usual high latitudinal ocean. However, when their temporal variations are compared between north and south sediment trap sites, a curious characteristic could be found. Spring increase in biogenic opal flux actually occurred earlier at the northern site (M4) than at the southern site (M6), although the sea ice retreated earlier at the southern site (Nakatsuka et al., 2004a). If the melting of sea ice causes the drop of ice algae downward and promotes the ice edge bloom of phytoplankton there, the increase in diatom flux must be recognized earlier at the southern site. The discrepancy between timings of sea-ice retreat and spring diatom bloom suggests that at least in the southern Sea of Okhotsk, sea ice does not contribute to the spring phytoplankton bloom directly. In contrast, the early diatom bloom in the northern site off northeast Sakhalin may indicate that materials and/or fresh water discharged from Amur River may act key roles to stimulate the spring diatom bloom supplying micro nutrients and/or creating stable pycnocline beneath the surface water.

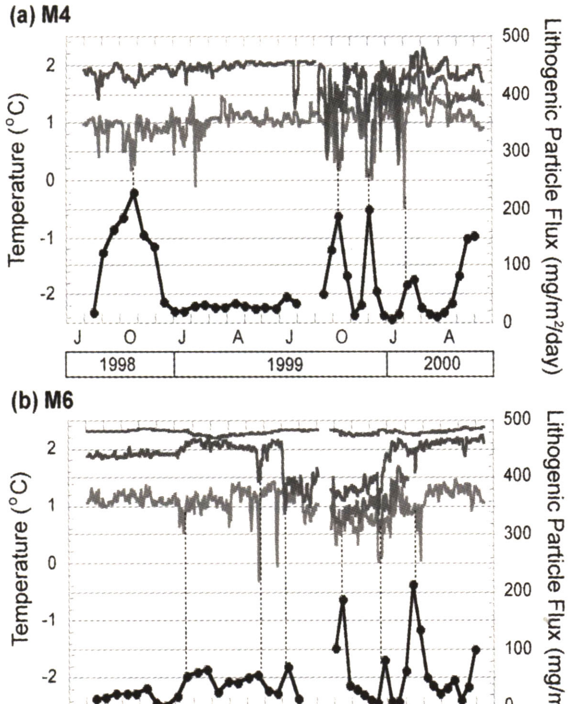

Figure 3. Temporal variations in the lithogenic particle flux (solid circles) at the lower traps of (a) M4 and (b) M6 sites, and daily average temperatures of intermediate layers (280, 370, 480m) at the mooring sites (gray lines).

2-2. WATER ANALYSES

Dissolved and particulate organic carbon (DOC and POC) measured for the water samples collected around the northern Sakhalin showed characteristic horizontal and vertical distributions (Nakatsuka et al., 2004b). DOC in the surface water has a clear negative relationship with salinity, indicating that DOC in surface waters of this area contains significant amounts of land-derived organic matter and Amur river water carries about 700 μ M of DOC into the Sea of Okhotsk. On the other hand, POC and DOC in the bottom layer on the shelf and the intermediate layers on the slope showed a negative correlation with temperature, suggesting that POC and DOC in the DSW are transported to pelagic area by the outflow of DSW being diluted by pelagic water masses. Finally, by the combination with physical oceanographic budget of DSW (Itoh et al., 2003), it can be concluded that the outflow of DSW supplies 13.6Tg of DOC and 0.9 Tg of POC from the continental shelf to OSIW (Fig.4), which are much larger than POC settling from-in-situ pelagic surface water, 0.2-0.5TgC (Nakatsuka et al., 2004b). This horizontal pathway which transports large amounts of organic matter into ocean interior feeds a huge community of heterotrophic organisms in the intermediate water of the Sea of Okhotsk (Sorokin and Sorokin, 1999).

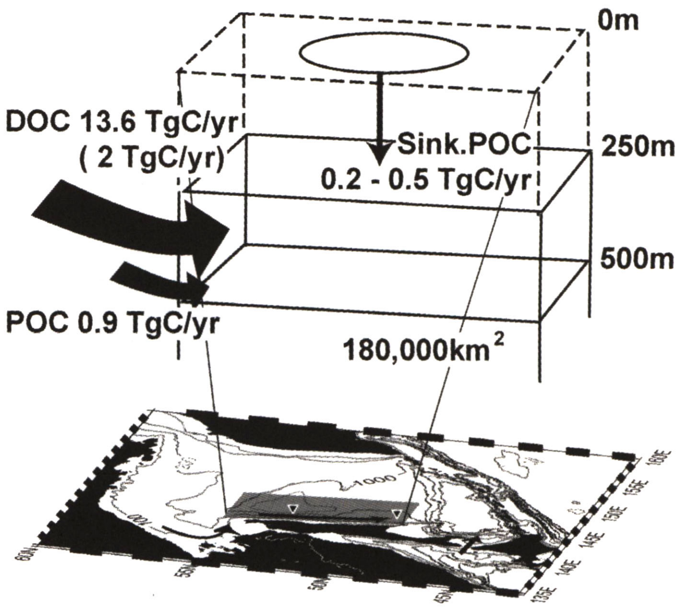

Figure 4. Fluxes of organic carbon into the intermediate layer off the east coast of Sakhalin Island. Inverted triangles on the map show the positions of sediment trap measuring the sinking POC flux

2-3. SEDIMENT CORES

In all the vertical profiles of three piston cores (Fig.5a), contents of total organic carbon (TOC) showed two maxima during last 40,000 years (Seki et al., 2004). One is the period of deglaciation, and the other is the late Holocene lasting to present. Although both of them were corresponding to the increases in production of primary producers, the main species increased were different between them (Fig.6). After the very low primary productivity in last glacial maximum at 20 kyr BP, coccolithopholid firstly increased during the deglacial period (Seki ei al., 2004). Diatom which is the main primary producer in the present Sea of Okhotsk began to increase at the early Holocene and it replaced the coccolithopholid about 5 kyr BP (Narita et al., 2002). The biogenic opal flux which is the indicator of diatom productivity was always higher at the western part of the Sea of Okhotsk than its eastern part (Fig.5b). In contrast, the $CaCO_3$ flux which is related to the coccolithopholid production was smaller at the western area although it may be affected by post-depositional dissolution (Fig.5c).

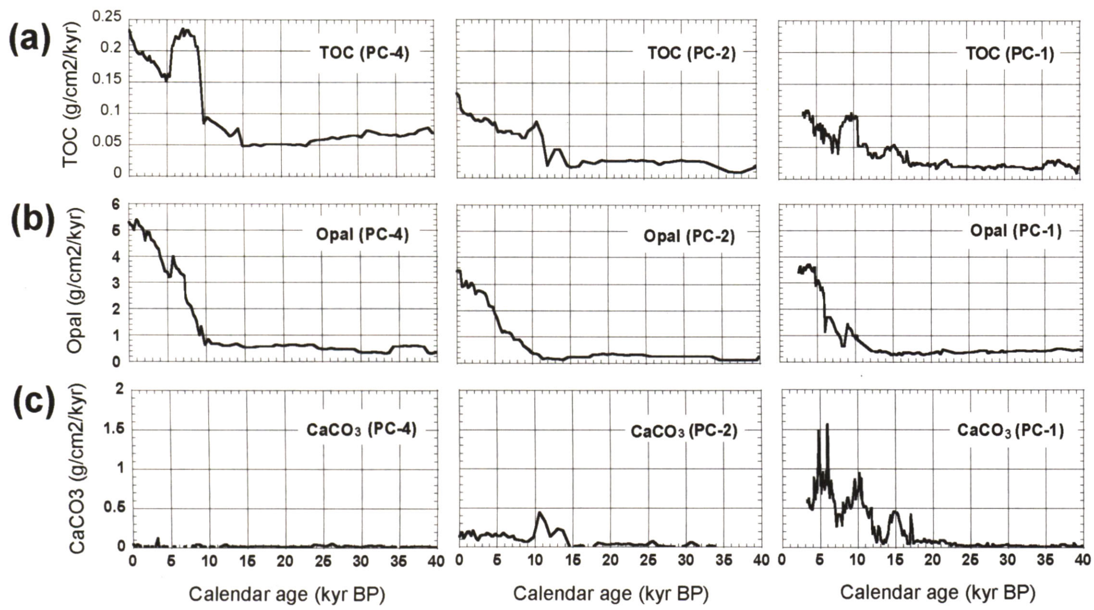

Figure 5. West-East distributions of historical changes in fluxes of TOC (a), Opal (b) and CaCO3 (c) during last 40 kyrs.

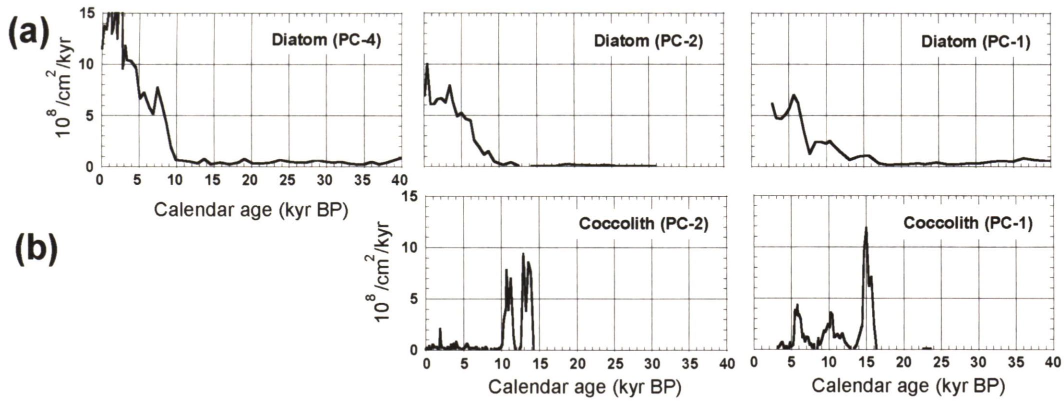

Figure 6. West-East distributions of historical changes in fluxes of valves of diatom (a) and coccolith (b) during last 40 kyrs.

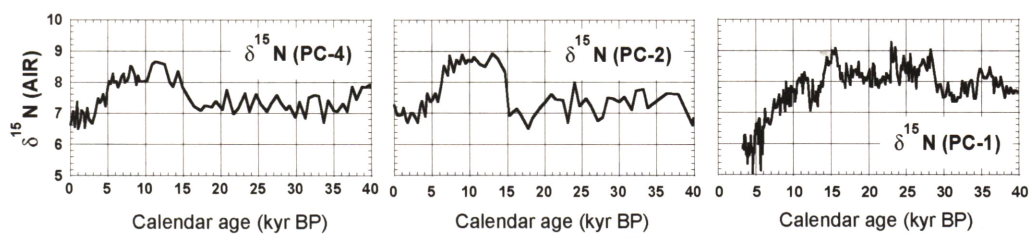

Figure 7. West-East distributions of historical changes in $\delta^{15}N$ during last 40kyrs.

In order to understand causes of these historical and horizontal variations of primary productivity in the Sea of Okhotsk, nitrogen isotopic ratios ($\delta^{15}N$) of sediment cores were analyzed (Fig.7). Because $\delta^{15}N$ of sinking particles in high latitudinal ocean usually reflect the nutrient utilization rate, which is the ratio of export production of nitrogen against the nitrate flux from subsurface to surface layers, the $\delta^{15}N$ of sediment can record past biogeochemical environments there (Nakatsuka et al., 1995). In general, the larger the nutrient utilization is, the higher the $\delta^{15}N$ of sediment becomes. In the central and western parts of the Sea of Okhotsk, the $\delta^{15}N$ was high only at the deglacial period, suggesting that the nutrient utilization rates were generally low there except for the deglacial period. In contrast, the $\delta^{15}N$ in the eastern parts of the Sea of Okhotsk showed constant high values until 10 kyr BP, suggesting the high nutrient utilization rate during glacial and deglacial periods. In Holocene, the $\delta^{15}N$ continuously decreased in the eastern area.

On the basis of these paleoceanographic proxy data, causes and results of the historical and spatial variations of primary productivity can be explained as follows. In the glacial period, the primary production was very low in all of the western, central and eastern parts of the Sea of Okhotsk. Although the low $\delta^{15}N$ values at western and central areas in the glacial period indicates that the prolonged sea ice cover suppressed the export production there (Sakamoto et al., 2005), the high $\delta^{15}N$ values of glacial periods at eastern area suggest that essential reason of low primary productivity at the glacial eastern area was the low nutrient availability due to strong halocline which is produced by enhanced sea-ice melting (Seki et al., 2005) and suppressing vertical exchanges of water between surface and subsurface layers. Because the sea ice spreads southward along the western coast and it finally melts at the southeastern region of the Sea of Okhotsk every year, it seems reasonable that the primary production of the western and central area at the glacial period is reduced by the enlarged sea ice cover, which on the other hand suppresses the vertical water mixing due to its melting at the eastern area. After the last glacial maximum, the $\delta^{15}N$ becomes high at all of the three cores during the deglacial period, indicating that nutrient utilization rate increased all over the Sea of Okhotsk. Because the main primary producer at that time was coccolithopholid which prefers warm and stable surface water mass, the high nutrient utilization rate during deglacial period was caused not only by the high primary production but also by the low nutrient availability. In the middle Holocene, the $\delta^{15}N$ becomes lower at all of the three sites, which indicates the increase of vertical water mixing, probably reflecting the global cooling after the warm climate in early Holocene. Because diatom needs silicate which comes from deeper layer of basin than nitrate or phosphate, the enhanced vertical mixing must have supported the growth of diatom at that time.

Conclusion

The biological productivity and material transport in the Sea of Okhotsk are actually characterized by the existence of seasonal sea ice, which does not only support the growth of ice algae attached but also transports the huge amounts of organic and inorganic matter into the ocean interior via the rejection of brine water., and on the other hand, had suppressed the primary productivity during glacial age. However, connections between sea ice and biological productivity in the Sea of Okhotsk have not been clarified thoroughly. Materials transported through intermediate layer by DSW outflow may stimulate the primary productivity around Kuril islands and Oyashio Region because they must contain large amounts of land-derived minor nutrients from Amur River, such as iron, and can be transported to far pelagic area from the coastal area without being consumed by organisms in surface water. Moreover, part of the intermediate water in the Sea of Okhotsk is finally entrained into surface layer by tidal mixing at Kuril straits, therefore, phytoplankton in Oyashio Region may actually utilize the materials in DSW. Such a remote connection between sea ice and biological production should be clarified in the near future.

Reference

Alfultis, M. A. and S. Martin, Satellite passive microwave studies of the Sea of Okhotsk ice cover and its relation to oceanic processes, 1978-1982, *Journal of Geophysical Research*, **92**, 13,013-13,028, 1987.

Fukamachi, Y., G. Mizuta, K. I. Ohshima, L. D. Talley, S. C. Riser and M. Wakatsuchi, Transport and its variability of dense shelf water revealed by long-term moorings off Sakhalin in the Sea of Okhotsk, *Journal of Geophysical Research*, **109**, C09S10, doi:10.1029/2003JC001906, 2004.

Gladyshev, S., S. Martin, S. Riser and A. Figurkin, Dense water production on the northern Okhotsk shelves: comparison of ship-based spring-summer observations for 1996 and 1997 with satellite observations, *Journal of Geophysical Research*, **105**, 26,281-26,299, 2000.

Itoh, M., K. I. Ohshima and M. Wakatsuchi, Distribution and formation of Okhotsk Sea Intermediate Water: An analysis of isopycnal climatological data, *Journal of Geophysical Research*, **108**, 3258, doi:10.1029/2002JC001590, 2003.

Kimura, N. and M. Wakatsuchi, Relationship between sea-ice motion and geostrophic wind in the Northern Hemisphere, *Geophysical Research Letter,* **27**, 3735-3738, 2000.

Kitani, K., An oceanographic study of the Sea of Okhotsk, particularly in regard to cold waters, *Bulletin of Far Seas Fishery Research Laboratory* **9**, 45-77, 1973.

Kowalik, K. and I. Polyakov, Tides in the Sea of Okhotsk, *Journal of Physical Oceanography,* **28**, 1389-1409, 1998.

Martin, S., R. Drucker, and K. Yamashita, The production of ice and dense shelf water in the Okhotsk Sea polynyas, *Journal of Geophysical Research,* **103**, 27,771-27,782, 1998.

Mizuta, G., Y. Fukamachi, K. I. Ohshima, and M. Wakatsuchi, Structure and seasonal variability of the East Sakhalin Current, *Journal of Physical Oceanography*, **33**, 2430-2445, 2003.

Nakatsuka,T., K.Watanabe, N.Handa, E.Matsumoto, and E.Wada, Glacial to interglacial surface nutrient variations of Bering deep basins recorded by $\delta^{13}C$ and $\delta^{15}N$ of sedimentary organic matter. *Paleoceanography*, **10**, 1047-1061, 1995

Nakatsuka, T., C. Yoshikawa, M. Toda, K. Kawamura and M. Wakatsuchi, An extremely turbid intermediate water in the Sea of Okhotsk : Implication for the transport of particulate organic carbon in a seasonally ice-bound sea, *Geophysical Research Letter*, **29**, 10.1029/2001GL014029, 2002.

Nakatsuka, T., T. Fujimune, C. Yoshikawa, S. Noriki, K. Kawamura, Y. Fukamachi, G. Mizuta and M. Wakatsuchi, Biogenic and lithogenic particle flux in the western region of the Sea of Okhotsk: Implications for lateral material transport and biological productivity. *Journal of Geophysical Research*, **109**, C09S13, doi:10.1029/2003JC001908, 2004a.

Nakatsuka, T., M. Toda, K. Kawamura and M. Wakatsuchi, Dissolved and particulate organic carbon in the Sea of Okhotsk: Transport from continental shelf to ocean interior. *Journal of Geophysical Research,* **109**, C09S14, doi:10.1029/2003JC001909, 2004b.

Narita, H., M. Sato, S. Tsunogai, M. Murayama, M. Ikehara, T. Nakatsuka, and M. Wakatsuchi, Biogenic opal indicating less productive northwestern North Pacific during the glacial ages. *Geophysical Research Letter*, **29**, 10.1029/2001GL014320, 2002.

Niebauer, H. J., V. Alexander and S. M. Henrichs, A time-series study of the spring bloom at the Bering Sea ice edge I. Physical processes, chlorophyll and nutrient chemistry, *Continental Shelf Research*, **15**, 1859-1877, 1995.

Ogi, M., Y. Tachibana, F. Nishio and M. A. Danchenkov, Does the fresh water supply from the Amur River flowing into the Sea of Okhotsk affect sea ice formation ?, *Journal of Meteorological Society Japan*, **79**, 123-129, 2001.

Ohshima, K. I., M. Wakatsuchi, Y. Fukamachi, and G. Mizuta, Near-surface circulation and tidal currents of the Okhotsk Sea observed with the satellite-tracked drifters, *Journal of Geophysical Research* **107**, 3195, doi:10.1029/2001JC001005, 2002.

Saitoh, S., M. Kishino, H. Kiyofuji, S. Taguchi, and M. Takahashi, Seasonal variability of phytoplankton pigment concentration in the Okhotsk Sea, *Journal of Remote Sensing Society of Japan,* **16**, 86-92, 1996.

Sakamoto, T., M. Ikehara, K. Aoki, K. Iijima, N. Kimura, T. Nakatsuka and M. Wakatsuchi, Ice-rafted debris (IRD) based sea-ice expansion events during the past 100 kyrs in the Okhotsk Sea. *Deep-Sea Research II* (in press)

Seki, O., M. Ikehara, K. Kawamura, T. Nakatsuka, K. Ohnishi, M. Wakatsuchi, H. Narita and T. Sakamoto, Reconstruction of paleoproductivity in the Sea of Okhotsk over the last 30 kyrs. *Paleoceanography*, **19**, PA1016, doi:10.1029/2002PA000808, 2004.

Seki, O., K. Kawamura, T. Sakamoto, M. Ikehara, T. Nakatsuka, and M. Wakatsuchi, Decreased surface salinity in the Sea of Okhotsk during the last glacial period estimated from alkenones, Geophys. Res. Lett., 32, L08710, doi:10.1029/2004GL022177, 2005.

Sorokin, Yu. I. and P. Yu. Sorokin, Production in the Sea of Okhotsk, *Journal of Plankton Research,* **21**, 201-230, 1999.

Sullivan, C. W., C. R. McClain, J. C. Comiso and W. O. Smith, Phytoplankton standing crops within an Antarctic Ice Edge assessed by satellite remote sensing, *Journal of Geophysical Research*, **93**, 12,487-12,498, 1988.

Talley, L.D., An Okhotsk Sea Water anomaly: implications for ventilation in the North Pacific, *Deep-Sea Research I,* **38**, S171-S190, 1991.

Talley, L. D., North Pacific Intermediate Water transports in the mixed water region, *Journal of Physical Oceanography*, **27**, 1795-1803, 1997.

Wong, C. S., R. J. Matear, H. J. Freeland, F. A. Whitney, and A. S. Bychkov, WOCE line P1W in the Sea of Okhotsk 2. CFCs and the formation rate of intermediate water. *Journal of Geophysical Research,* **103**, 15,625-15,642, 1998.

Yasuda, I., K. Okuda, and Y. Shimizu, Distribution and modification of North Pacific Intermediate Water in the Kuroshio-Oyashio Interfrontal Zone, *Journal of Physical Oceanography*, **26**, 448-465, 1996.